DDSim: A Multiscale Damage and Durability Simulation Strategy

Digital Twin Workshop
NASA Langley Research Center

John Emery, Sandia National Laboratories
Prof. Tony Ingraffea, Cornell University

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Outline for the Talk

Goal: Improved prognosis / diagnosis

- **Motivation & broad overview**
  - Why do we need a new fatigue life prediction tool?
- **The <u>probabilistic</u>, <u>hierarchical</u>, <u>multiscale</u> approach**
- **DDSim Level I – Reduced-order filter**
  - Approach
  - Results & Performance
- **Level II – Automated crack propagation**
  - Approach
  - Results
- **Level III – Multiscale simulation (Dr. Hochhalter)**
  - In brief
- **Conclusions**

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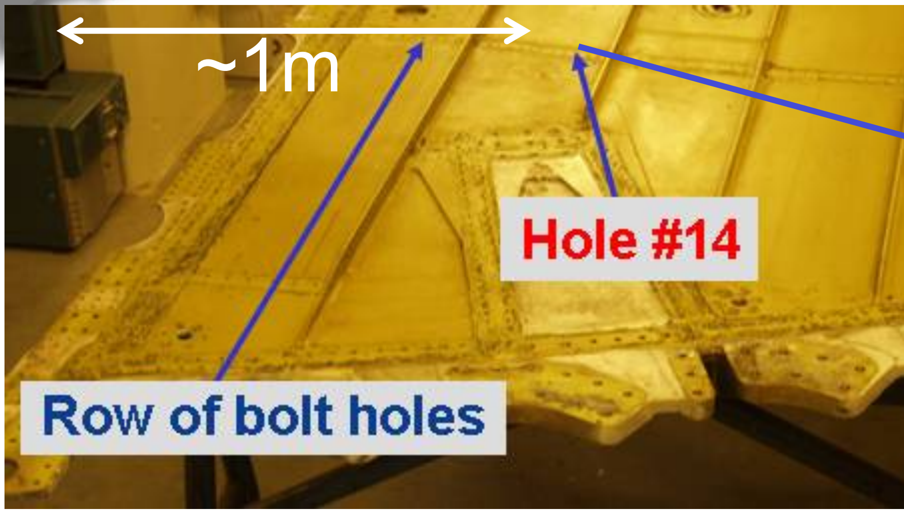
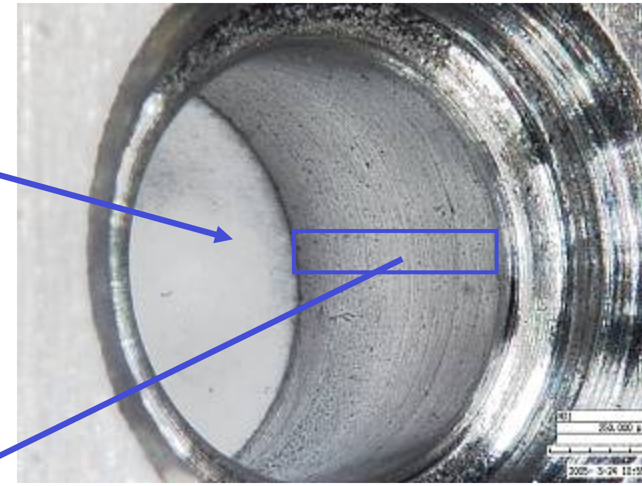
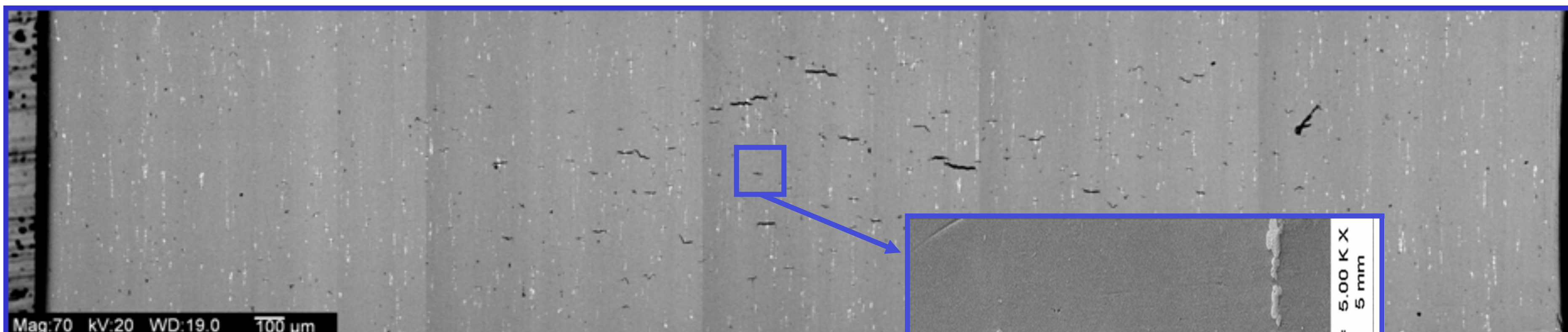
Fatigue is Inherently *Multiscale* and *Stochastic*!







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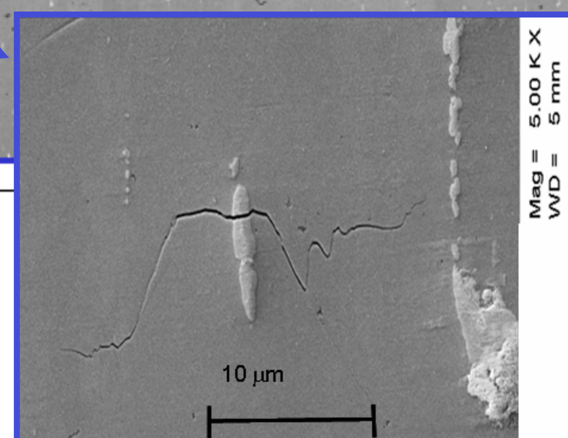
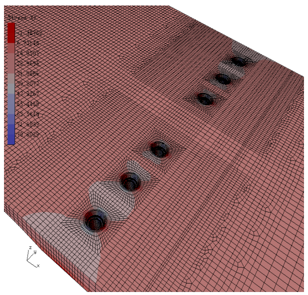


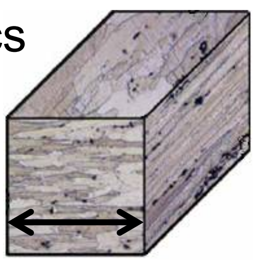
The Challenge

Random input



Finite element model of structure including boundary/environmental conditions

Material system & pertinent microstructural statistics



~100 μm

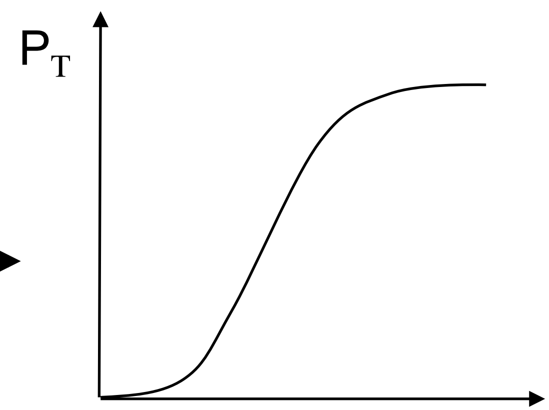
Best available physics-based damage models

$$\dot{g}^{\alpha} = G_o \left(\frac{g_s - g^{\alpha}}{g_s - g_o} \right) \sum_{\beta} 2 \left| \mathrm{S}_{ij}^{\alpha} \, \mathrm{S}_{ij}^{\beta} \right| \left| \dot{\gamma}^{\beta} \right| ,$$

$$\dot{\gamma} = \sum_{\alpha=1}^{\mathrm{N}_{ss}} \left| \dot{\gamma}^{\alpha} \right|$$

DDSim

Probabilistic life prediction w/ confidence bounds



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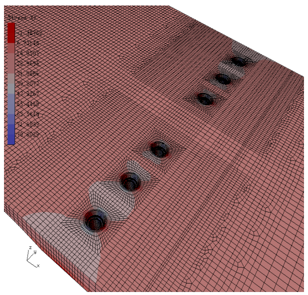

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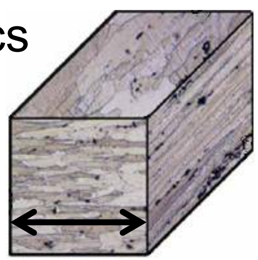

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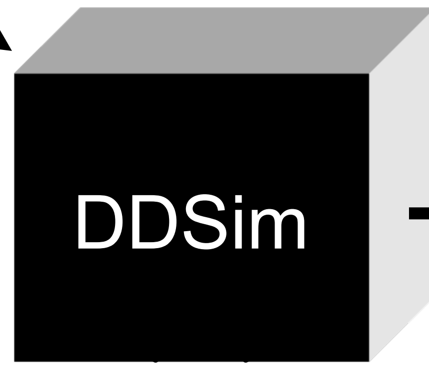

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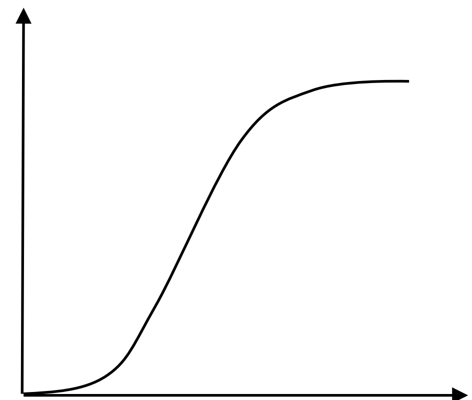

Plan for ever evolving technologies:
faster computers, better experimental techniques, more efficient numerical approaches, etc., etc.

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A Hierarchical Approach

Assuming: $N_{total} = N_{MLC} + N_{MSC}$

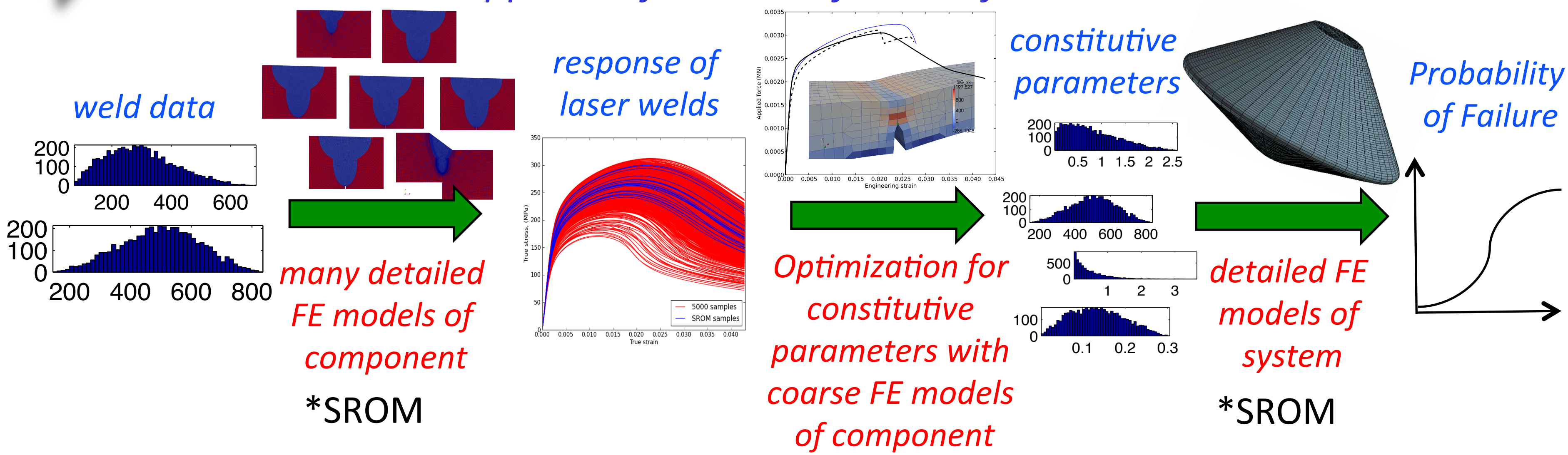
A multiscale approach with 3 hierarchical levels:

- **Level I**: A fast, analytical, reduced-order filter to determine life-limiting hot-spots in complex structures and approximate N_{total}
- **Level II**: Traditional continuum fracture mechanics, FRANC3D, to compute the life of the structure consumed by growth of microstructurally Large cracks ($\mathbf{N_{MLC}}$)
- **Level III**: Multiscale simulation to compute the life of the structure consumed by incubation, nucleation and propagation of microstructurally small cracks ($\mathbf{N_{MSC}}$)
- **Level IV:** (plan for evolving technologies)

Take full advantage of "what we do now" and develop better numerical methods / physical models

A Brief Excursion – Common Interests

Hierarchical approach for ductile failure of laser welds – Level I



- Simulation of joining (mechanically fastened, bonded, welded, etc.) technology
- Combining data from variable-fidelity models
- Large-scale computation of full-scale models (time dependent solution of many DOF models)
- Simulation of response and damage to complex environments (severe thermal, acoustic, corrosive, embrittlement) and loading, (e.g., hypersonic) requires multi-physics modeling
- Modeling of corrosion (stress and chemical state)
- Limited results from experiments – interpolation/extrapolation
- Multi-site, multi-component, system-level failure mechanisms
- Damage evolution models starting from low length scales
- Verification and validation all length and time scales (full large-scale and local) and loading environments
- Robust digital representation of microstructure

(see p. 5 Roadmap)

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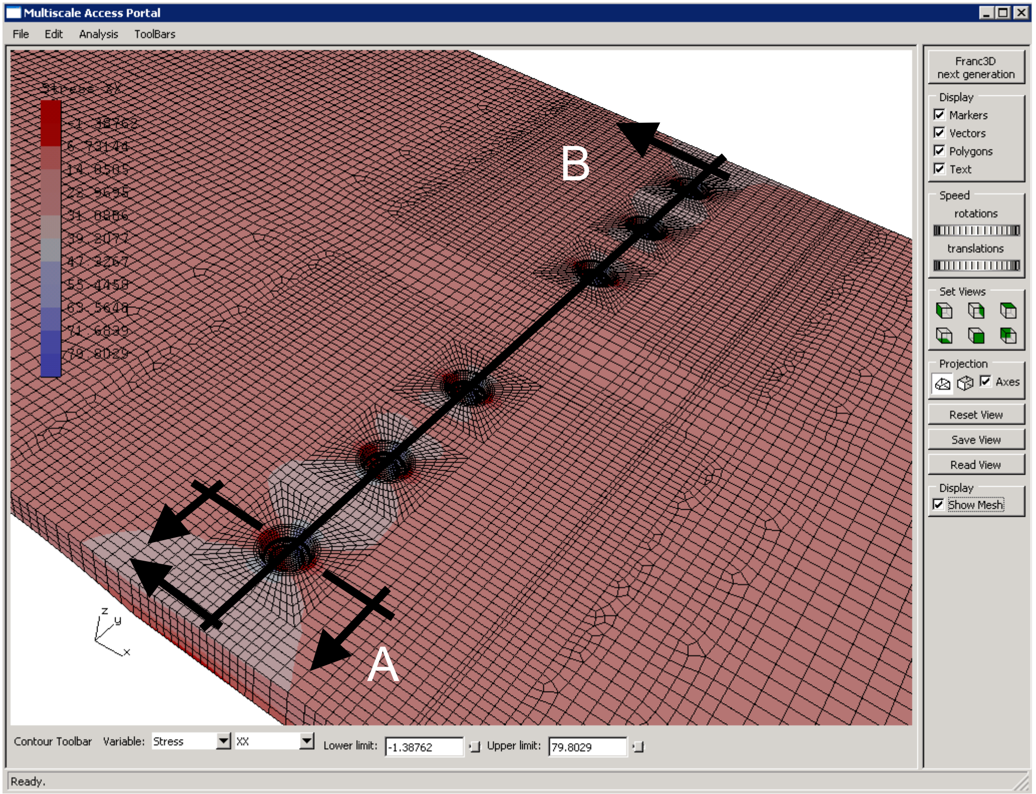
DDSim Level I

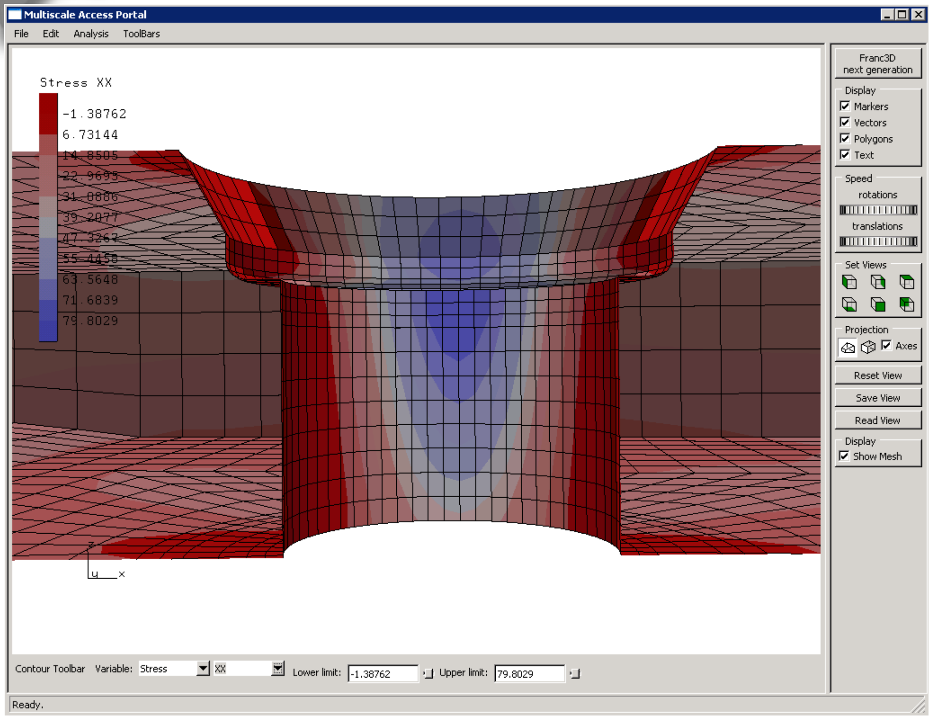


Stress field contour plot:
Rib-stiffened element

How to map:

Stress → Life prediction?

DDSim Level I

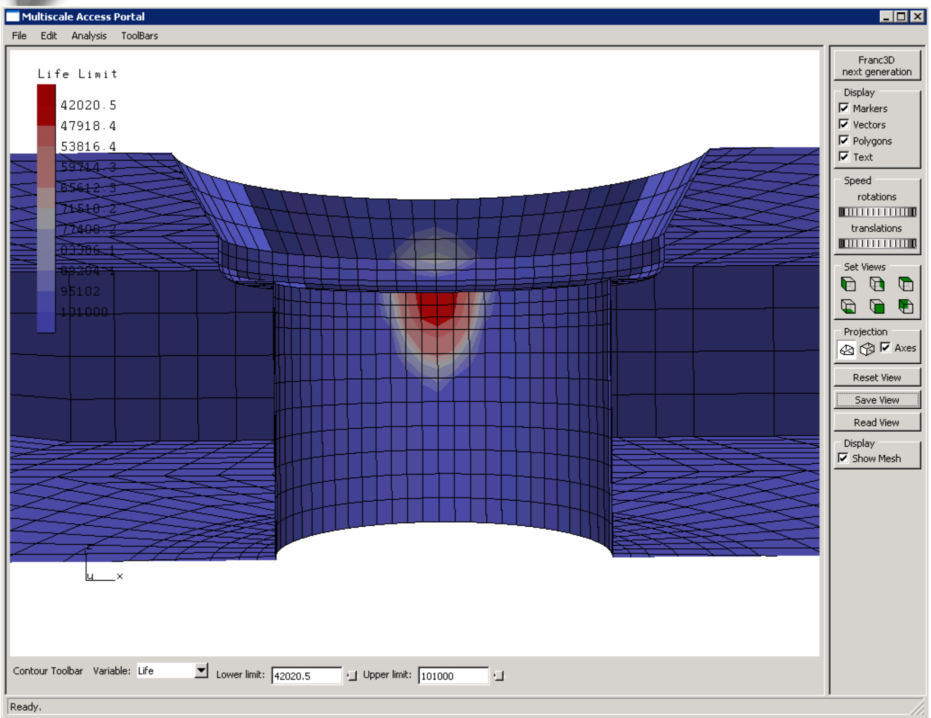


Stress field contour plot:
x-section A,
Rib-stiffened element

How to map:

Stress → Life prediction?

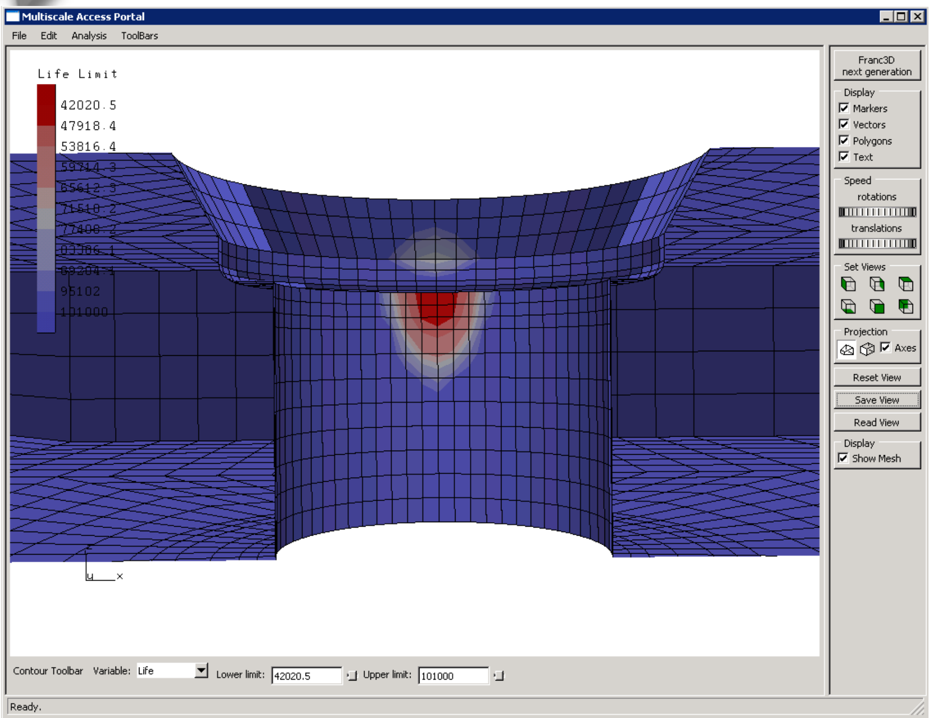
DDSim Level I



Life prediction contour plot
on original FE Mesh
(63,974 surface nodes, average a_i=4μm)

- Analytical solutions & field data from undamaged FEM used to estimate service life limited by *damage* at a large number of *possible* origins (each mesh node).
- Initial flaw size from statistical distribution (eg. particle x-sectional area).
- These *damage origins* do **NOT** become part of the geometrical model in Level I.
- These *damage origins* do **NOT** interact with each other.
- These simplifications readily allow parallel processing.

DDSim Level I



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Key Ideas for Level I:
High Volume, High Automation, Probabilistic, & Conservative First Order Analysis

Level I is a low-fidelity, multiscale, probabilistic prediction

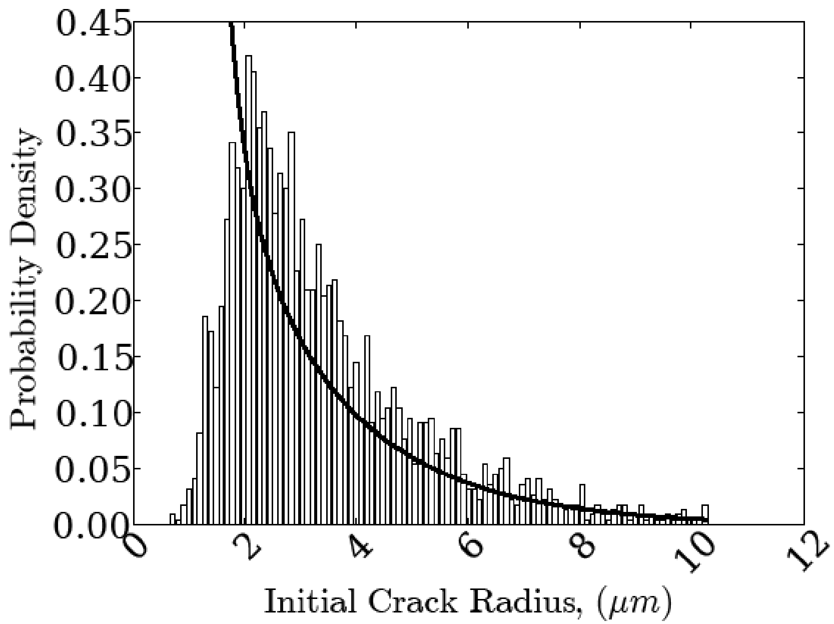
Density of Particle Diameter, μm

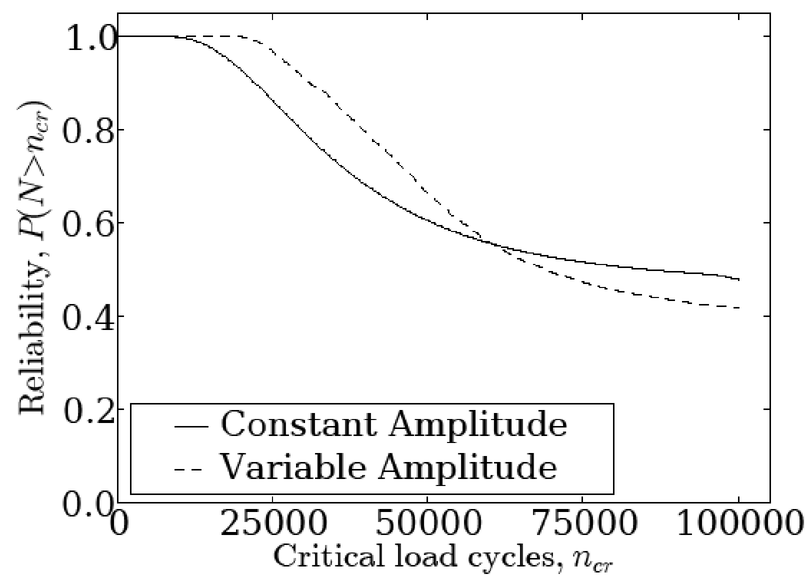
Particle radius randomly selected from a list of observed particles

Reliability, P(N>n)

$$P(N>n) = \sum_{i}^{m=\#\,nodes} P(N>n \mid a_i)P(a_i)$$

$$P(a_i) = {}^{q_i}\!/_{B};\; B = \sum_i^m q_i \qquad q_i = \#\text{ broken particles at node i}$$





Under fatigue spectrum: 63,974 FE nodes (i.e. initial flaw locations); 10,000 samples of initial flaw size (w/ particle filter); 20,802 - 99,999 cycles min & max computed life; ~20 min on 170 dual 3.6 GHz processors w/ 4GB RAM

DDSim Level II

Fully 3D crack growth simulation at "hot spots":

- Explicit representation of crack surface in FE model geometry
- Automatically inserted at "hot spots" determined by Level I analysis

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Level I Life prediction contour plot
(x-section B slide 13)

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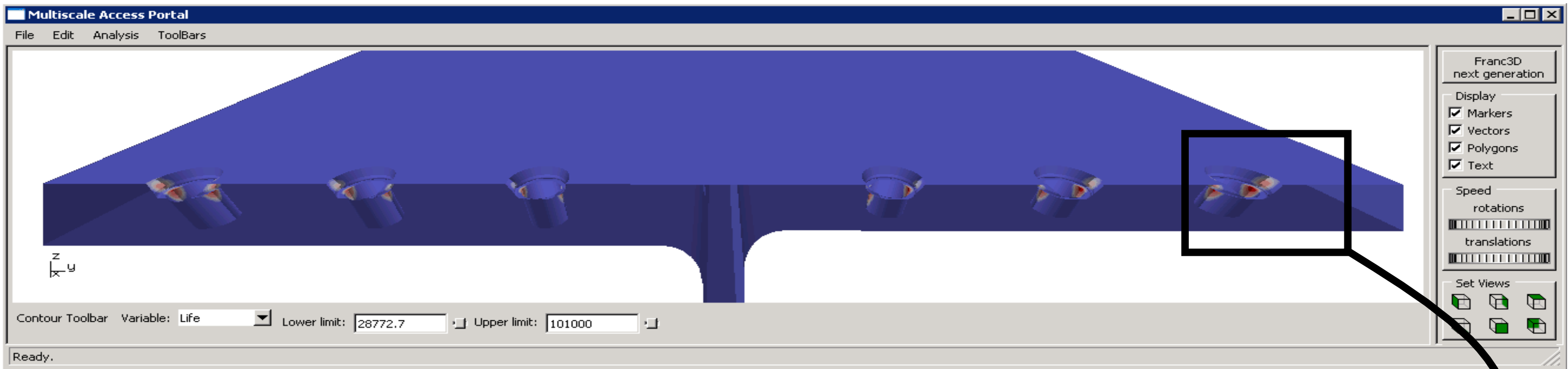
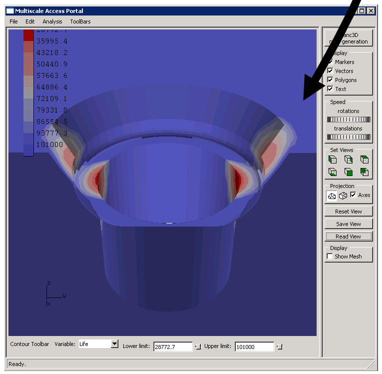


Level I Life prediction contour plot (x-section B slide 13)



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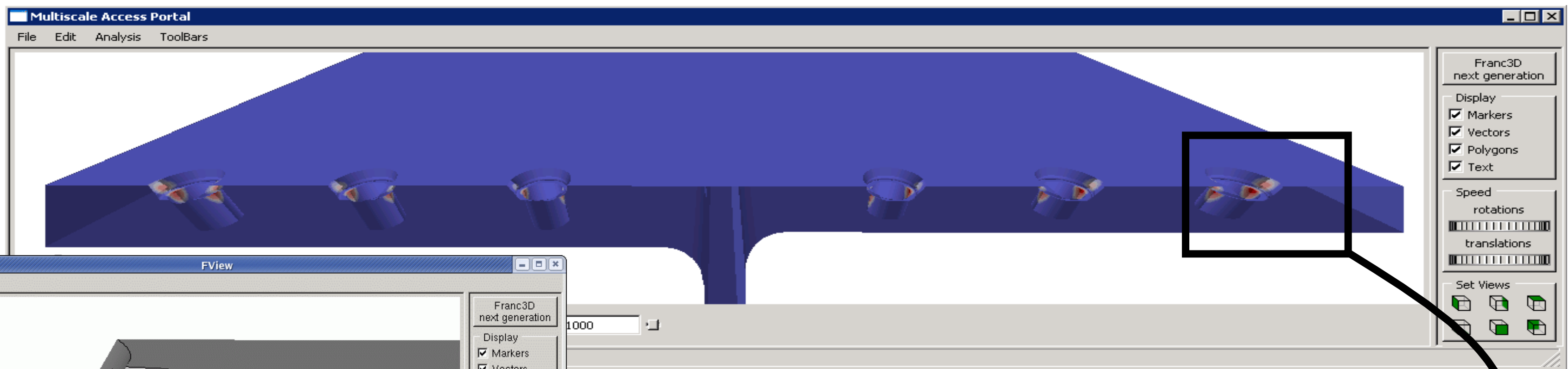

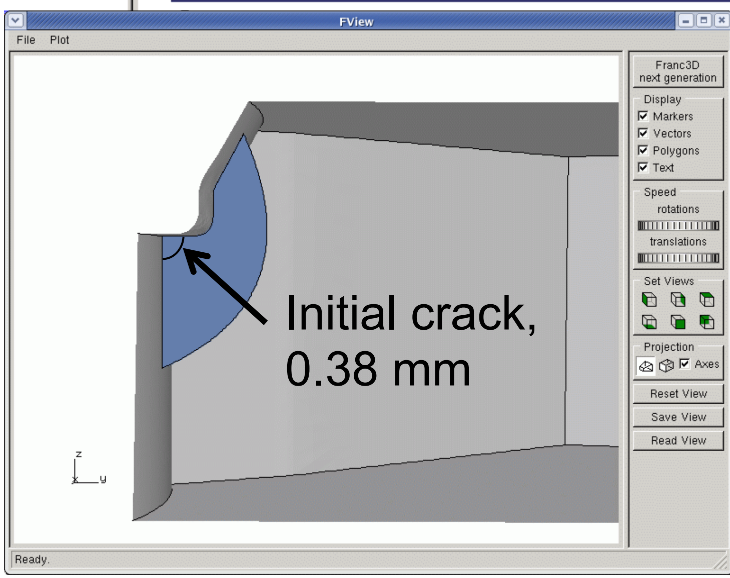

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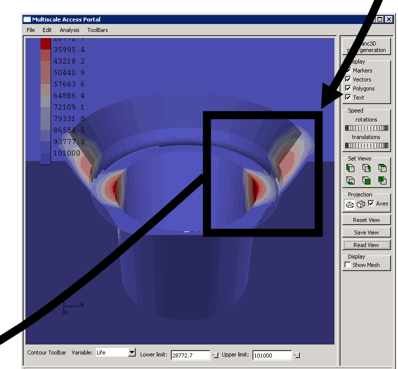

Automatically inserted, grown and remeshed crack, step 8

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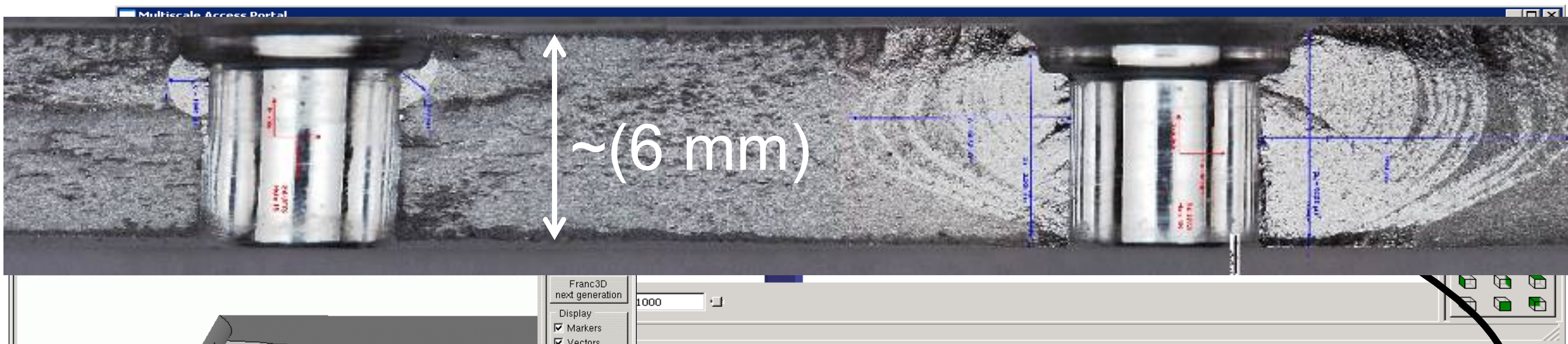

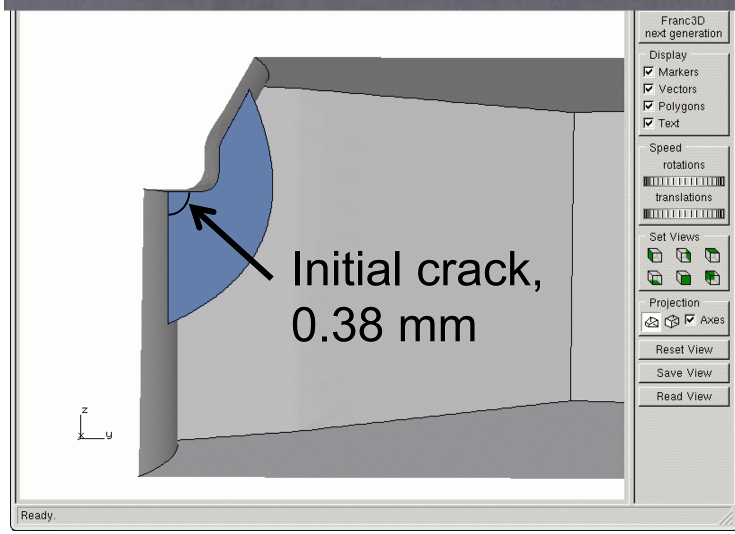

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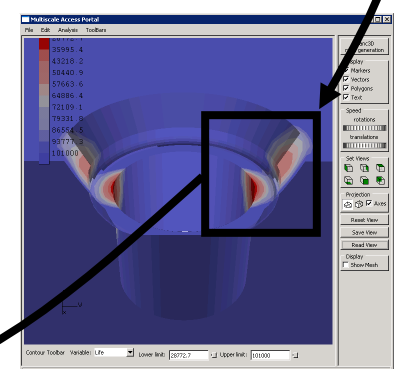

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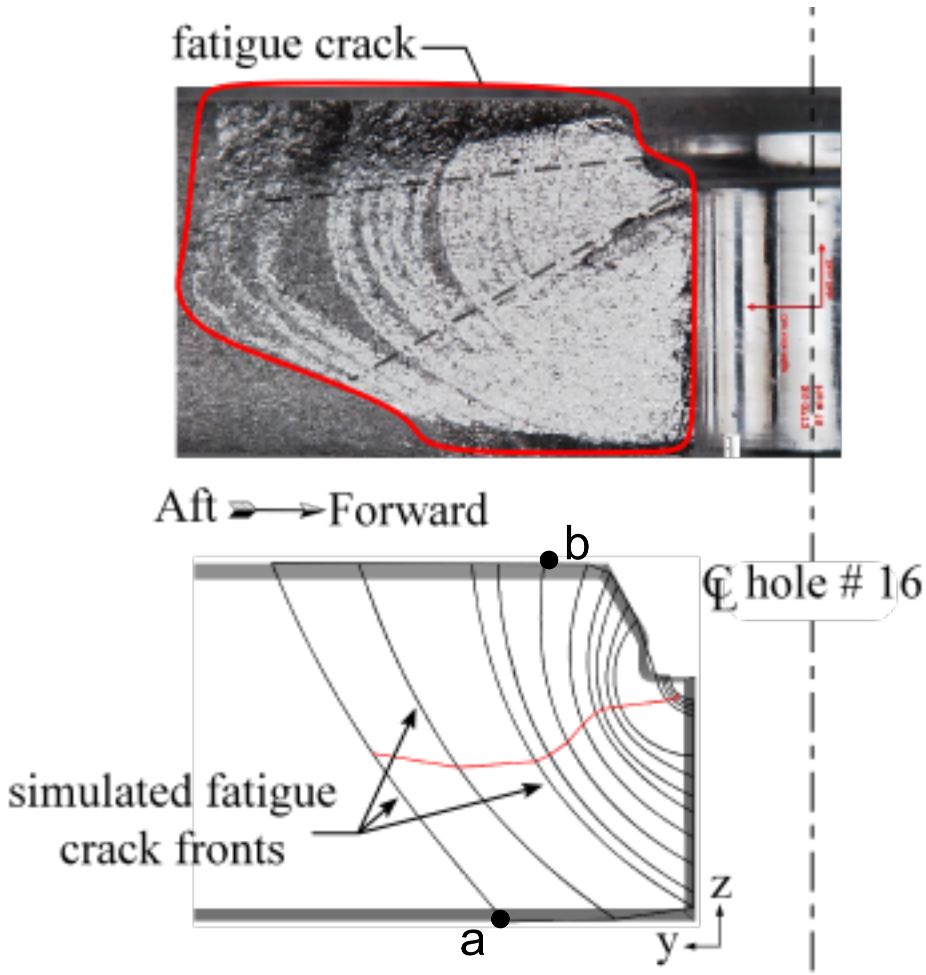
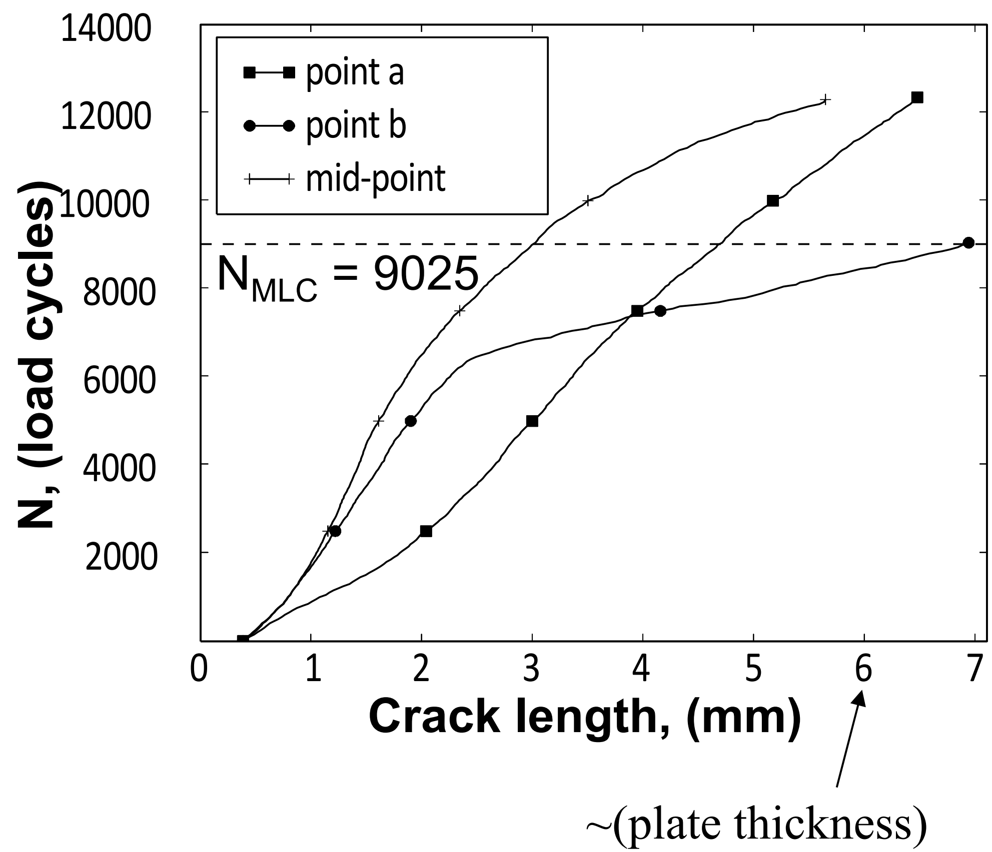
Level II Results

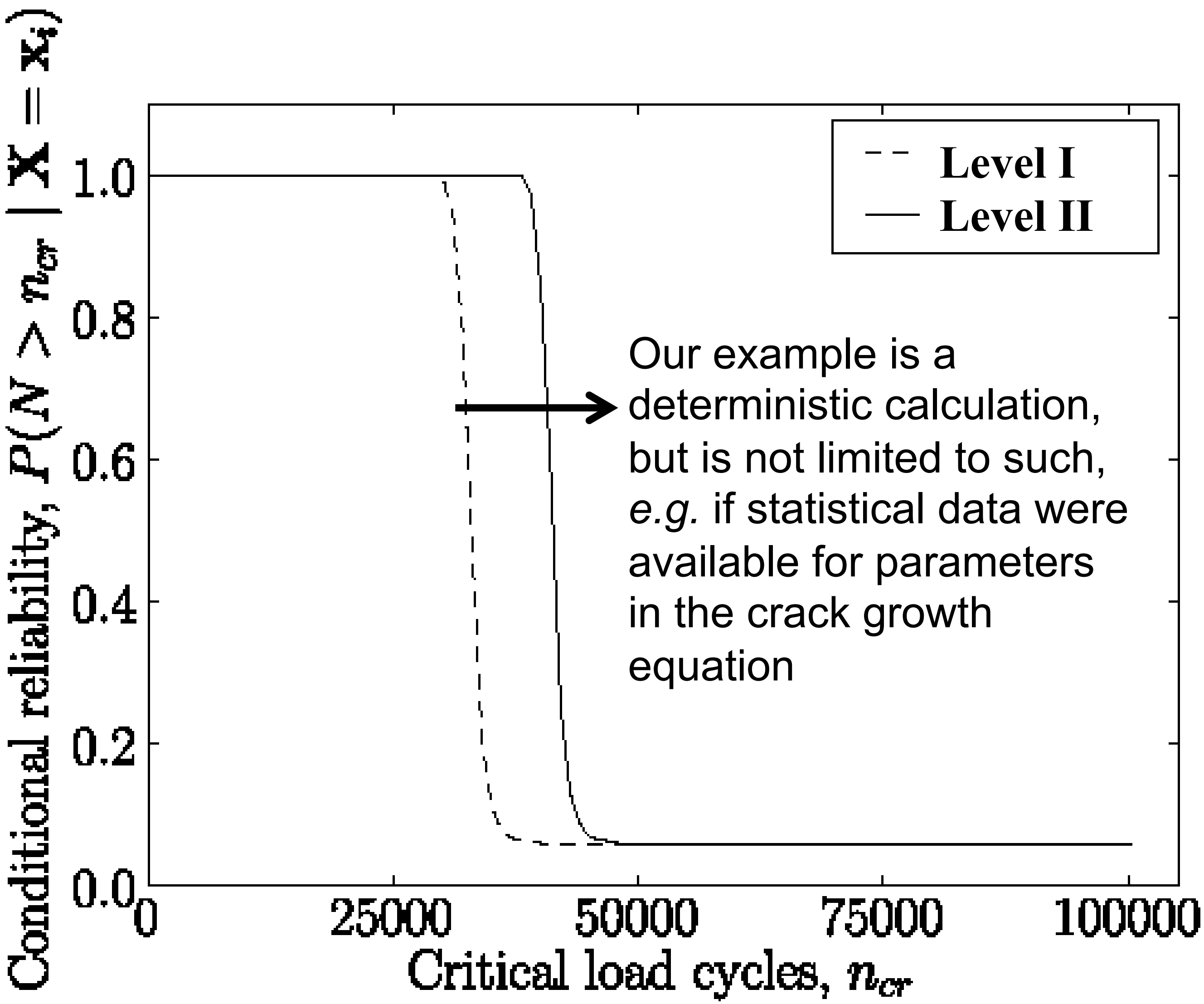


Low fidelity N_{MLC} = 803 cycles

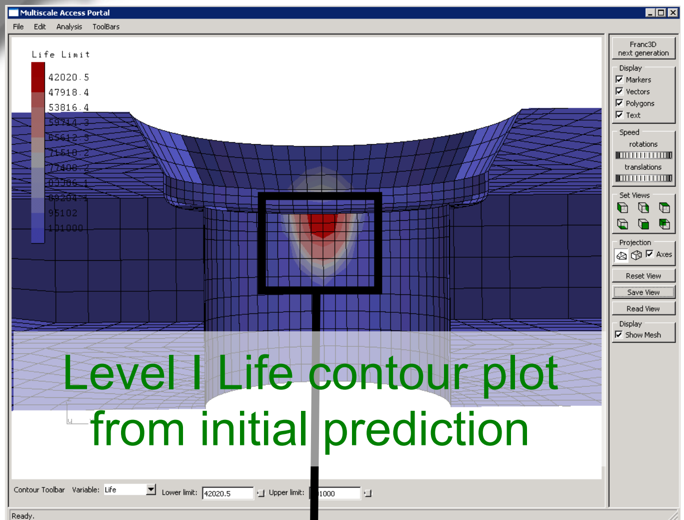
High fidelity N_{MLC} = 9025 cycles



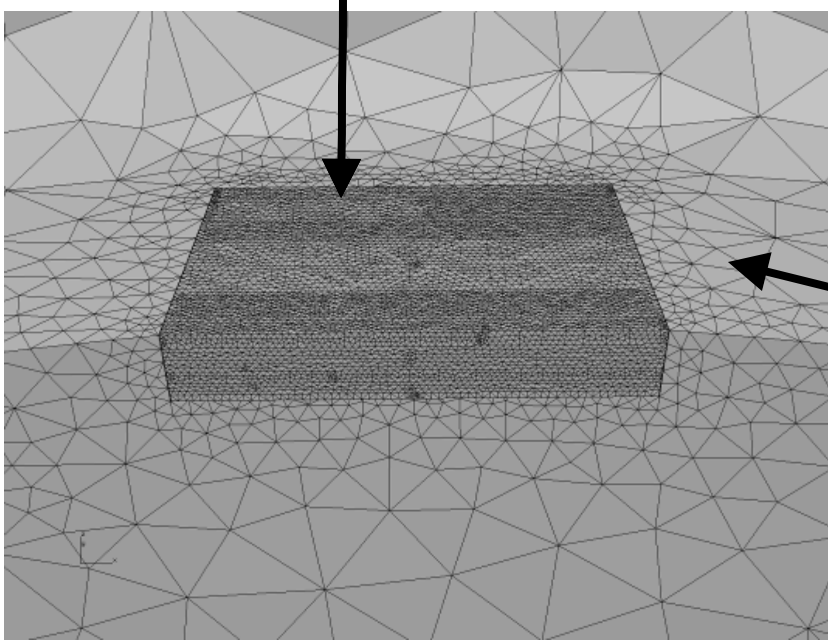
Level II Conditional Reliability at Hot-spot



Level III - Concurrent multiscale w/ L2 coupling

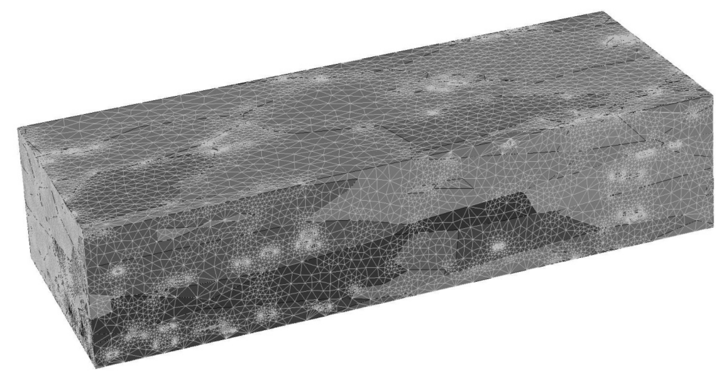


Level I Life contour plot from initial prediction



With a first-order, probabilistic prediction completed, focus on the “hot spots” to increase the accuracy of the N_{MSC} prediction using:

- Concurrent multiscale (there are other methods)
- Representative digital microstructure
- Best available physics
- High performance parallel computing



High resolution meso-scale model

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Conclusions

Our assumption was: $N_{total} = N_{MLC} + N_{MSC}$

- **DDSim Level I provides a *high volume*, *highly automated*, *probabilistic*, and *conservative* life prediction (N_{total}) for real structures & locates areas of high interest for the Level II & III simulations**
- **Level II uses the current best-practice fracture mechanics life predictions methodologies for high fidelity N_{MLC}**
- **The Level III multiscale simulation will incorporate state-of-the-art microstructural models and best-available physics to account for microstructural stochasticity resulting in a high fidelity estimate of N_{MSC}**
- **DDSim, as a multiscale system, will provide microstructurally educated reliability predictions for real structures**

Acknowledgments

Essential Contributors:

- Dr. Bruce Carter, Fracture Analysis Consultants
- Dr. Gerd Heber, Oxford University
- Dr. Jacob Hochhalter, NASA LaRC
- Dr. John Papazian, Northrop Grumman
- Dr. Wash Wawrzynek, Fracture Analysis Consultants
- The Cornell Fracture Group

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